

A COMPARATIVE STUDY ON EVALUATION METHODS OF EMERGENCY VENTILATION STRATEGIES

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ABSTRACT

With the occurrence of indoor terrorism attacks and the accidental release of toxic chemicals, people have paid more attentions on such emergency events in recent years. The effective evaluation method of emergency ventilation strategies could help people find out the accurate way to control the ventilation system, and reduce the total loss during the event. In this article, two methods to evaluate the effect of ventilation are compared. One is based on Efficiency Factor of Contaminant Source (EFCS). The other is based on Exposure Risk (ER) and Population Risk (PR). By using these indices of ventilation efficiency, 6 cases with different ventilation style in a full-scale room in which the occupant distribution is prescribed have been investigated numerically. The results show that the two evaluation methods can function well on evaluating the performance of emergency ventilation and should be used properly for different purposes.

KEYWORDS

Evaluation method, Emergency ventilation, Occupant evacuation model, Exposure Risk, Population Risk

INTRODUCTION

Nowadays, ventilation systems are widely used for climate control in various kinds of spaces, such as rooms, underground tunnels, vehicles and even aeroplane cabins (Awbi 2003, Li and Chow 2003, Spengler and Wilson 2003). The purpose of emergency ventilation is to remove pollutant suddenly released indoors effectively. As the chemical and biological attack by terrorists occurs frequently in buildings in recent years, it has become a threat to the public environment throughout the world. A previous study has shown that improving airflow pattern maybe a better solution for pollutant removal (Marshall et al. 1996, Chen et al. 2005). It means the emergency ventilation system, if properly designed, could help reduce the total loss during such indoors attacks. As we know, the effective evaluation method of emergency ventilation strategies could help people find out the accurate way to control the ventilation system. Therefore, the study on evaluation method plays a very important role on influencing people's safety and health under the situation of emergency.

Since the current indices to evaluate ventilation effectiveness are only appropriate for evaluating the ventilation performance in a steady state, such as air age, air exchange efficiency (AEE) (Sandberg and Sjoberg 1983, Sandberg 1983), contamination removal efficiency (Sandberg 1981), a scale for measuring ventilation effectiveness in a room (SVE) (Murakami 1992, Kato et al. 1994), integrated accessibility of contaminant source (IACS) (Li and Zhao 2004, Zhao et al. 2004b) and so on, they cannot be used for the purposes of emergency ventilation, which do not reflect the influence of contaminant to occupants whose distribution changes with the time during the emergency events. In order to determine an emergency ventilation strategy, Cai et al. (2007a) proposed a new concept, Efficiency Factor of Contaminant Source (EFCS), which includes EFCS1~EFCS3. These series indices evaluate the ventilation efficiency based on the relative exposure of occupants in the events. With EFCS indices, the ventilation strategy could be evaluated without knowing the intensity and components of the source. In order to consider the different exposure to occupants from different kinds of contaminants, a new method based on Exposure Risk (ER) and Population Risk (PR) is proposed in this paper. The contaminant exposure to occupants is predicted numerically in a 3-dimensional room and the two evaluation methods are compared with these cases. By comparing two evaluation methods with these cases, the optimal ventilation strategy could then be proposed in different situations.

EVALUATION METHODS

The whole process of determining ventilation strategy to protect the indoor environment against contamination includes examining the room function and the capability of the ventilation system, providing suitable emergency ventilation strategies for different situations by using CFD analysis, obtaining the distribution of indoor occupant during emergency and analyzing the ventilation forms by using the evaluation methods to select the best one.

Exposure Cell

In order to define EFCS, ER and PR, the concept of Exposure Cell (EC) should be introduced. Exposure cell, which is an abstract spatial concept, represents

the indoor spatial volume that caused occupant exposure (Cai et al. 2007b). According to different research objectives, the volume occupied by a single person can be taken as one exposure cell, namely EC_i ($i = 1, 2, \dots, M$). The contaminant concentration in the exposure cell EC_i at time t is represented by $\bar{C}_i(t)$. The number of indoor occupants in EC_i at time t is represented by $PNC_i(t)$ ($PNC_i(t) \geq 0$).

Efficiency Factor of Contaminant Source (EFCS)

The indices of EFCS reflect the relative influence of indoor contaminant source to occupants in any periods of time (Cai et al. 2007a). These series indices are defined as:

$$EFCS1_i(\tau) = \frac{\int_0^\tau \bar{C}_i(t)PNC_i(t)dt}{\bar{C}_R \int_0^\tau PNC_i(t)dt} \quad (1)$$

$$EFCS2_j(\tau) = \frac{\int_0^\tau \bar{C}(CN_j(t),t)dt}{\bar{C}_R \tau} \quad (2)$$

$$EFCS3(\tau) = \frac{\sum_{i=1}^M \int_0^\tau \bar{C}_i(t)PNC_i(t)dt}{\bar{C}_R \sum_{i=1}^M \int_0^\tau PNC_i(t)dt} \quad (3)$$

In Eq. (1)~(3), $EFCS1_i(\tau)$ indicates the influence degree of contaminant source to the occupant who passed the Exposure Cell EC_i ($i = 1, 2, \dots, M$) in the period τ ; $EFCS2_j(\tau)$ reflects the influence degree of contaminant source to the j^{th} occupant in the time periods of τ ; while $EFCS3(\tau)$ is the influence degree of contaminant source to the whole occupants in the period τ . On evaluating the performance of emergency ventilation, the focus is the occupants, not the Exposure Cell. In this Paper, the indices of $EFCS2\sim 3$ should be introduced respectively. \bar{C}_R is the average contaminant concentration of air outlet in the steady state condition. $CN_j(t)$ is the number of exposure cell for which the j^{th} person stays at time t . If $CN_j(t)=i$, then $\bar{C}(CN_j(t),t) = \bar{C}_i(t)$. τ_j represents the total stay time of the j^{th} occupant, if $\tau \geq \tau_j$, then set $\tau = \tau_j$.

Exposure Risk (ER) and Population Risk (PR)

The concept of ER and PR states the absolute influence of indoor contaminant source to occupants in any periods of time. These series indices are defined as:

$$TAC_j = \frac{\int_0^\tau \bar{C}(CN_j(t),t)dt}{\tau} \quad (4)$$

$$ER_j = \begin{cases} 0 & \text{if } TAC_j \leq AEGL1 \\ \frac{TAC_j - AEGL1}{AEGL2 - AEGL1} \times L & \text{if } AEGL1 < TAC_j < AEGL2 \\ L & \text{if } TAC_j = AEGL2 \\ \frac{(TAC_j - AEGL2) \cdot (1 - L)}{AEGL3 - AEGL2} + L & \text{if } AEGL2 < TAC_j < AEGL3 \\ 1 & \text{if } AEGL3 \leq TAC_j \end{cases} \quad (5)$$

$$PR = \frac{\sum_{j=1}^N ER_j(\tau_j)}{N} \quad (6)$$

In Eq. (4)~(6), TAC_j indicates the average exposure concentration of the j^{th} occupant in the time periods of τ , ER_j reflects the j^{th} occupant's injured degree of the contaminant toxicity in the periods τ , PR is the average injured degree of the whole occupants in the period τ . $AEGL1\sim 3$ are acute exposure guideline levels published by Environmental Protection Agency (EPA). $AEGL1$ indicates exposures causing discomfort but are not disabling and are transient and reversible upon cessation of exposure. While above $AEGL2$, it is predicted that the general population could experience irreversible or other serious, long-lasting adverse health effects or an impaired ability to escape. $AEGL3$ is the death threshold. L is the coefficient which reflects the toxic efficiency of $AEGL2$. Its numerical value should be decided by toxicologists. In this paper, L is evaluated as 0.5 provisionally. N is the number of the whole occupants.

SIMULATION METHODS

Simulation Tool

In order to analyze the diffusion of contaminant in the ventilation room, a well-validated CFD program, STACH-3 (Zhao et al. 2003b, Li and Yan 1995), is adopted to study the problems numerically. This CFD program was widely used in previous studies (Zhao et al. 2000, Zhao et al. 2001, Zhao et al. 2002, Zhao et al. 2003a, Zhao et al. 2004a, Zhao et al. 2004c). To account for the turbulent flow in a room, a zero-equation turbulence model (Chen and Xu 1998) is used in this case.

Occupant Evacuation Model

Research on modeling human movement and behavior in emergency event has been underway for many years. CA (Cellular Automata) is a discrete, decentralized and spatially extended system consisting of large numbers of simple identical components with local connectivity (Yang et al. 2004). In this paper, a 2-dimensional Cellular Automata model (Yang et al. 2003), which has been widely applied in traffic flow and fire evacuation investigation, is used for reference. Based on the classical CA model, Song et al. (2005) proposed a new CA model. In this new model, the occupants'

evacuating characteristics involving suddenly released pollution during the event are included. It also considered the friction, repulsion and attraction of one person against another person or against building. The new model can simulate the time of evacuation exactly, and describe the classical phenomena during the process of occupant evacuation perfectly, and therefore is used here.

CASE DESCRIPTION

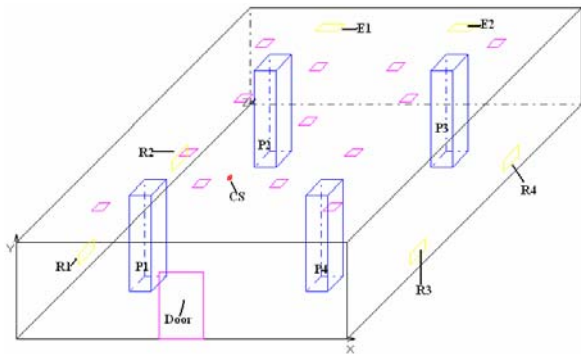


Figure 1 Schematic of the simulation room

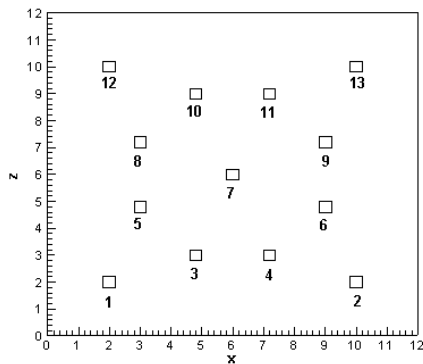


Figure 2 Schematic of the supply air diffusers

The above-mentioned model (Fig. 1~2) is used to simulate the effect of an emergency ventilation strategy in a 3-dimensional room under isothermal condition. The room is 12 m (X) long, 3.5 m (Y) high and 12 m (Z) wide. The contaminant source is assumed to be located at (X, Y, Z) = (2m, 8m, 0.1m), whose emission rate is 3g/s. The kind of contaminant is Chlorine Dioxide. In Fig. 1, R1~R4 is the exhausts for normal ventilation, E1~E2 is the exhausts for emergency ventilation, CS is the contaminant source, P1~P4 is pillars.

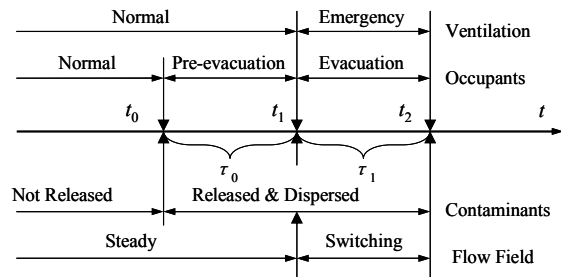


Figure 3 Developing process of emergency ventilation (Cai et al. 2007a)

Fig. 3 shows the development process of emergency ventilation. At time $t_0 = 0$, the contaminant source began to emit. At time $t_1 = 300s$, people began to evacuate, meanwhile the ventilation system switched to emergency mode. There were 80 persons stayed randomly in the room at time t_1 . The exposure cells are divided in the height of respiration region ($Y=1.4m\sim 1.8m$), whose size is $(\Delta X, \Delta Y, \Delta Z) = (0.4m, 0.4m, 0.4m)$. The time step of evacuation is 0.5s. Table 1 shows the different kinds of ventilation modes. Case 0 is the normal mode. Case 1~ Case 6 are emergency modes.

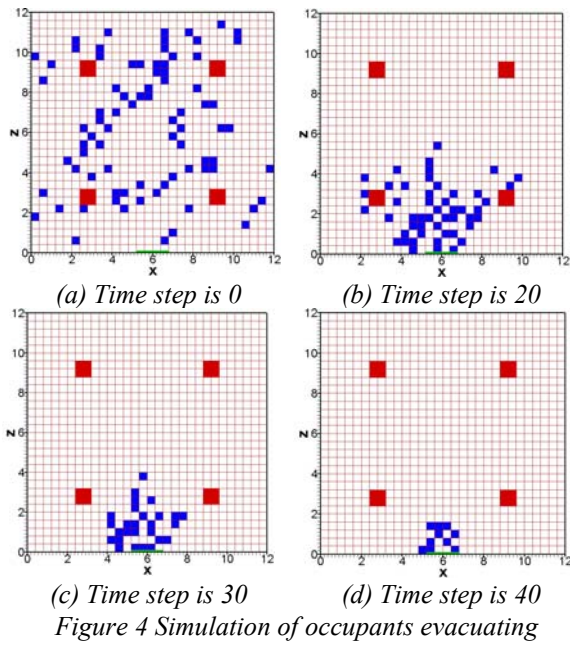
Table 1 Emergency ventilation modes for the cases

CASE NO.	OPENINGS IN OPERATION	VERTICAL AIR INLETS VELOCITY [M/S]	VERTICAL AIR OUTLETS VELOCITY [M/S]	AIR CHANGE RATE [ACH]
Case 0	O1-O13, R1-R4	0.4	— —	6
Case 1	O1-O6, R2,R4	0.875	— —	6
Case 2	O2,O6,O9,O13, R1,R2	1.3125	— —	6
Case 3	O10-O13, R1-R4	1.3125	— —	6
Case 4	E1,E2(door open)	— —	2.625	12
Case 5	O1-O6, E1,E2(door open)	0.875	2.625	12
Case 6	O2,O6,O9,O13, E1,E2(door open)	1.3125	2.625	12

RESULTS AND DISCUSSION

The simulation result shows that, it spends 47 time steps that all the people evacuate out from the room. The evacuation time is 23.5s. Fig. 4 (a)-(d) give the stages at the time-step of 0, 20, 30 and 40,

respectively. The red blocks are the pillars location, which can not be occupied by any evacuating people. The green line shows the location of the door, the only exit of the room. In the available area, the blue boxes are the cells which are occupied by persons at this time, while the white ones are empty.



Evaluated by EFCS

The $EFCS3(\tau_1)$ indices of all the cases are shown in Fig. 5. The smaller the value of $EFCS3(\tau_1)$, the less the total influence of contaminant source to indoor occupants and the safer the people. As showed in Fig. 5, when the air change rate is 6 ACH, the best result is Case 2; when the air change rate is 12 ACH, Case 6 is the best one. If evaluated by EFCS3, Case 2 is the optimization of all modes. Fig. 6 shows the $EFCS2_j(\tau)$ indices in the time period of $t_1 \sim t_2$.

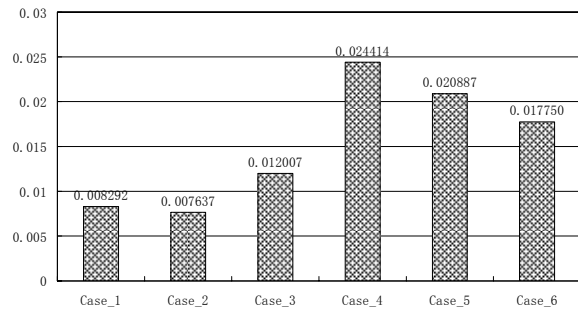


Figure 5 Indices EFCS3 for each case during the evacuation process

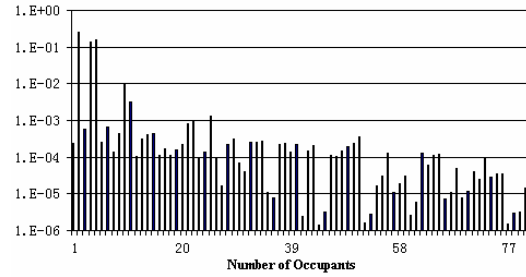
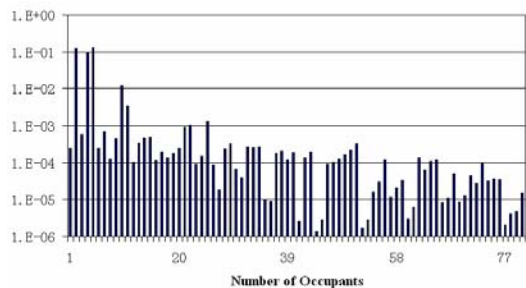


Figure 6 Indices EFCS2 for each occupant during the process of evacuation (Case 2 and Case 3)

Evaluated by ER and PR

Table 2 Acute Exposure Guideline Levels (AEGLs) Results of Chlorine Dioxide (10-min) [2002]

LEVELS	AEGL-1	AEGL-2	AEGL-3
[mg/m3]	0.41	3.9	8.3

Table 2 give the AEGLs results of Chlorine Dioxide (EPA. 2000–2002). The $ER_j(\tau)$ indices in the time period of $t_1 \sim t_2$ are shown in Fig. 7. If $ER_j(\tau_1)=0$, the occupants could not feel discomfort; if $0 < ER_j(\tau_1) < 0.5$, exposures caused discomfort; if $0.5 \leq ER_j(\tau_1) < 1$, the general population could experience irreversible adverse health effects or an impaired ability to escape; if $ER_j(\tau_1)=1$, people will die.

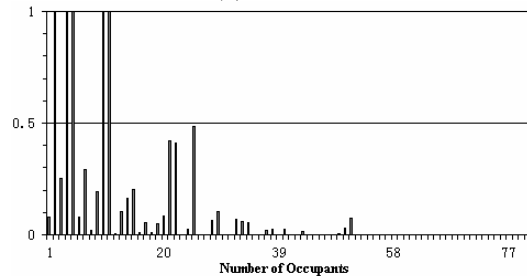
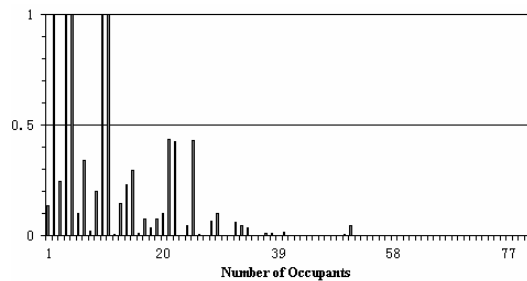


Figure 7 Indices ER for each occupant during the process of evacuation (Case 4 and Case 5)

Table 3 shows the number of occupants in different injured degrees by toxicity. According to the above-mentioned data, Case 4 is the optimization of all modes, which is based on the indices of ER.

Table 3 The occupants' number in different toxic injured degrees

NO.	DISCOMFORT	SERIOUS SCATHE	DEATH
Case 1	39	1	5
Case 2	35	1	5
Case 3	34	1	5
Case 4	32	0	5
Case 5	34	0	5
Case 6	31	1	5

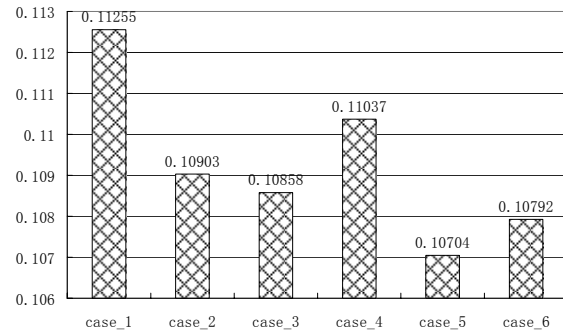


Figure 8 Indices PR for each occupant during the process of evacuation

As showed in Fig. 8, Case 5 is the optimization of all modes, which is evaluated by the indices of PR.

Table 4 The results of different evaluation indices

INDICES	CASE 1 ~ CASE 3 (6 ACH)	CASE 4 ~ CASE 6 (12 ACH)	CASE 1 ~ CASE 6
EFCS	Case 2	Case 6	Case 2
ER	Case 3	Case 4	Case 4
PR	Case 3	Case 5	Case 5

Table 4 indicates the results using different evaluation method are not uniform. This can be explained as follows:

The essential meaning of EFCS is the relative influence degree of indoor environment to occupants. Here, relativity means the actual exposed concentration of occupants during evacuation compared with \bar{C}_R in the same ventilation mode. When the emission strength of the contaminant source is a fixed value, the higher the air volume from inlets, the lower \bar{C}_R is. Because of the different air change rate, the value of $EFCS3(\tau_1)$ in Case 4~Case 6 is much higher than that in Case 1~Case 3. Therefore, if using the indices of EFCS to evaluate modes, the air volume from inlets of each mode must be equal or comparable.

It can be seen from Fig. 6 and Table 3 that the number of injured occupants in case 3 is less than that in case 2, but the actual exposed concentration of single person during evacuation in case 3 is much higher than that in case 2. Accordingly, when the purpose of emergency ventilation is to reduce the actual exposed concentration, case 2 is better than case 3; when the purpose is to control the injured occupants' number, case 2 is better than case 3.

Comparing Fig. 7 and Table 3, we can find that the number of injured occupants in case 4 is less than that in case 5, but the toxic injured degrees of single person during evacuation in case 4 is much deeper than that in case 5. So when the purpose is to control the injured occupants' number, case 4 is better than

case 5; when the purpose is to mitigate the injured degree, case 5 is optimization. Therefore, different evaluation indices should be used for different purposes.

CONCLUSION

Based on the occupant evacuation model and two kinds of evaluation methods, six cases with different ventilation modes have been studied numerically. From this study, the following conclusions are drawn:

1. The indices of EFCS reflect the relative influence of indoor contaminant source to occupants in any periods of time. When the indices of EFCS are used to compare the different ventilation modes, the air volume from inlets of each mode must be equal or comparable.
2. The indices of ER and PR consider the actual exposed concentration of occupants during evacuation. The value directly reflects the occupant injured degree. When the two indices are used to evaluate ventilation modes, the intensity and components of the source should be known.
3. Different evaluation methods should be used for different purpose. When Aiming to reduce the actual exposed concentration, we should use EFCS; when hoping to control the injured occupants' number, we should use ER; when asking for the lowest toxic injured degree, PR is the best choice.

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